

Simulation Test Beds for the Space Station Electrical Power System

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Abstract

NASA Lewis Research Center and its prime contractor are responsible for developing the electrical power system on space station. The power system will be controlled by a network of distributed processors. Control software will be verified, validated, and tested in hardware and software test beds. Current plans for the software test bed involve using real time and non-real time simulations of the power system. This paper will discuss the general simulation objectives and configurations, control architecture, interfaces between simulator and controls, types of tests, and facility configurations.

1 Introduction

NASA Lewis Research Center and its prime contractor are responsible for developing the electrical power system on space station. The power system will be controlled by a network of distributed processors. Control software will be verified, validated, and tested in hardware and software test beds. Software test bed verification and validation will reduce the risk of costly hardware failures. Current plans for the software test bed involve using real time and non-real time simulations of the power system. These simulations will address specific aspects of testing.

This paper will discuss the current space station power system design, next generation test bed configuration, simulations in support of the test bed, and the configuration of the simulation facility (EPS Automation Lab).

2 Space Station Power System Design

The power system on Space Station has been designed to provide power on demand to Space Station systems and scheduled power to experiments. The current design is the result of the Phase B Space Station design effort over the past few years.

2.1 Distribution Architecture

The overall end-to-end distribution subsystem (Figure 1.) includes all the elements necessary to process and control the power system from the photovoltaic and solar dynamic sources to the user interface. Users include housekeeping for the overall station operation, attached payloads and module payloads such as materials processing experiments. The Power Management and Distribution (PMAD) architecture includes the main inverters in the PV integrated equipment boxes and the frequency changers in the SD electrical equipment boxes and extends to the Power Distribution and Control Assemblies

(PDCAs), the secondary distribution cabling, and the the load converters or power supplies. The management and control of the overall power system is described in the following section. For the Initial Operational Capability (IOC) station, the main inverters in each of two photovoltaic module electrical equipment assemblies will convert 160 VDC power (from PV arrays) to 440 V, 20 kHz, single phase power and the frequency changers in the SD electrical equipment boxes will convert 208 V, 1200 Hz, three phase power (from SD source) to 440 V, 20 kHz, single phase power. This power will be regulated to 2 1/2% at the user interface. The four sources will be synchronized to a common frequency to allow paralleling of sources and minimize electromagnetic interference. Two 160 VDC control busses directly from the energy storage in the photovoltaic modules will distribute power to all embedded processors and controllers to insure that the power system is configured correctly for assembly and start-up. A dual ring architecture (Figure 2.) is used for both the upper and lower keels, booms, and the modules. The 20 kHz power is transfered across the alpha gimbal via a roll ring assembly.

2.2 Controls Architecture

Control of subsystems and systems aboard space station are distributed in nature. Figure 3. shows a general diagram of the various systems on the space station. The Data Management System (DMS) coordinates the distributed systems such as fluids, thermal and power, and also systems such as Guidance, Navigation and Control (GN&C), Communications and Tracking (C&T), Environmental Control and Life Support Systems (ECLSS), etc. The DMS polls the various systems and sends the appropriate commands. The control architecture for the power system is distributed because of the multiple power sources and the decentralized load areas in the modules and on the upper and lower boom (refer to Figure 2.). Figure 4. shows the control architecture of the power system. The Power Management Controller (PMC) coordinates all system functions such as the power generation systems (photovoltaic and solar dynamic), the power distribution system, and user loads in their various operating modes. Also the PMC communicates with the DMS by sending required data (i.e. status) and also carries out DMS commands related to power. The Power Management Controller communicates with the Node Switching Assemblies (NSAs), Main Bus Switching Assemblies (MBSAs), Power Distribution Control Assemblies (PDCAs), and the AC Switching Assemblies (ACSAs) (outboard of the alpha joint) over a control data bus. The AC Switching Assembly provides a means of communication to the Photovoltaic and Solar Dynamic Source Controllers. These source controllers control the the various subsystems within the power generation units. Data from these lower level controllers (in subsystems) is passed up to higher level controllers and eventually to the PMC. Control functions are divided appropriately among these controllers for proper efficiency. These functions include subsystem health monitoring, system reconfiguration, fault detection and isolation, etc.

2.3 Power System Operation

The objective of power system operation is to meet the power requirements of all users. The only constraints to this objective are the safety and protection of the Electrical Power System (EPS) and other Space Station systems, or manual override by the flight or ground crew.

2.3.1 Normal Operating Conditions

Under normal operating conditions, automatic load shedding does not occur. Sufficient reserve peaking capacity will be provided to accommodate normal variations in power usage.

Space Station core systems such as fluids, thermal, DMS, ECLSS, C&T, GN&C, etc. will receive continuous power on demand. Exceptions to this rule will be made only on a case-by-case basis. Examples of such exceptions might be intermittent large loads such as airlock pumps or reboost propulsion

which could be operated on a predetermined schedule. However, these loads will still receive power on demand if needed for contingencies.

Experiments which require large amounts of power will be scheduled. The EPS in cooperation with the Operations Management System (OMS) will determine the optimum schedule. The user will be notified of his schedule via the DMS.

2.3.2 Abnormal Operating Conditions

Abnormal operating conditions occur during power generation system failures, faults in the user load or the power distribution system, and failures of the Space Station.

During power generation system failures the action taken by the power system depends on the amount of power generation capacity lost. If the lost capacity is small, the remaining power generation equipment is operated at increased capacity, up to safe operating limits, to make up the loss. No immediate impact is felt by the users. The only impact is in long term scheduling. In the event that the remaining equipment cannot make up the loss without exceeding safe limits, load shedding will be performed.

During faults in the user load or the power distribution system, the distribution system will be reconfigured to isolate the fault. The distribution switchgear will monitor all aspects of the power distribution network in order to detect faults. If the fault occurs in the distribution system, the power management system will redirect power flow such that there is a minimal interruption of power to the users. If the fault occurs in the user loads, power to the loads will be cut until the user has found the cause of the fault, has made necessary repairs, and has requested for power to be turned back on.

2.3.3 Load Scheduling Procedures

Since the power system cannot provide power to all loads, all the time, power therefore must be scheduled. There are many factors that must be considered when scheduling power which include crew activity schedules, other distributed system resources such as thermal, user experiment resource requirements, and power availability. The OMS responsibility for managing space station operations makes it a source of information to schedule power efficiently along with the power system power management and control. Initially scheduling of power will be primarily a ground support function with some scheduling done automatically aboard space station. As experience grows the scheduling process will be automated.

In the ground support scenario, the ground support centers will generate schedules using several tools. These tools include scheduler packages (possible expert system), a link to the OMS for overall space station management information (resource allocation schedules) via the DMS, and user load requirements (resource information). These schedules will be reviewed by the OMS for conflict resolution.

In the automated scenario, the computers resident in the distributed system will generate schedules without human intervention. The resulting schedules will be reviewed by the OMS for conflict resolution.

2.3.4 Load Shedding Procedures

In the event that emergency load shedding needs to be done, the PMAD system has contained within it a prioritized list of loads that can be dropped. This list has been negotiated with the space station (OMS) so there is no doubt that the overall station objectives are being preserved. These priorities have been established when the user requested power via the transaction management system. Once it is determined that certain loads must be shed to maintain orderly station operation the action can proceed in the following way. Low priority loads that have data interfaces to the DMS will be notified by the PMAD system over the DMS bus that they must power down or power off as the case may be. This will allow these loads to save themselves in an orderly manner and prevent any damage that may

be caused by loss of power. In the event that the load does not respond with a given length of time, or it does not have a DMS interface, its power will be turned off via command from the PMC over the power management control bus. One final note, all of the automated functions just described can be overridden by the crew at any time.

2.3.5 Operation Execution

The controls of the power system will execute the power system operations described in the preceding sections via a hierarchical control architecture. The Power Management Controller will coordinate the lower level controllers and also communicate with the Data Management System. The lower level controllers such as the NSAs, MBSAs, PDCAs, ACSAs, etc. will receive commands from the PMC and control the switchgear appropriately.

3 Next Generation Test Beds

Currently there are several test beds in operation. The 20 kHz photovoltaic test bed in Figure 5. demonstrates the 20 kHz distribution technology. It consists of a DC source, an inverter which converts DC to 20 kHz AC, load converters, and loads. Figure 6. shows the solar dynamic test bed that demonstrates a distributed control architecture. It consists of a mid frequency source (SD alternator), a frequency changer which converts 1200 Hz, three phase AC power to 20 kHz, single phase power, a ring distribution architecture, load converters, loads, and a distributed control network. Also included in the SD test bed is a DC source and an inverter. The next generation test bed (Integrated PMAD Breadboard, IPB) will incorporate the designs of the previous test beds into a single power system which looks fundamentally like the current space station power system design described previously.

3.1 Distribution Architecture

The proposed distribution architecture for the IPB (Figure 7.) is similar to that of the space station power system. The major differences are that there are a limited number of loads, namely Power Distribution and Control Assemblies (PDCAs), no Node Switching Assemblies (NSAs), no solar dynamic sources, less battery storage and the use of battery simulators, and no roll ring power transfer devices in the IPB. Functionally the IPB will operate as does the power system.

3.2 Controls Architecture

The proposed controls architecture for the Integrated PMAD Breadboard (Figure 8.) is also similar to that of the space station power system. The major differences are that there are less PDCA controllers, no NSA controllers, no controls for the SD sources and therefore no SD source controller, no controller redundancy, and therefore reduced data traffic on the control busses.

4 Simulation Support

Simulations will be used to support the design and testing of the Integrated PMAD Breadboard. These simulations are of various fidelity, configuration, and execution times. The following sections discuss the various simulation objectives, simulation configurations, controls configuration, interfaces between simulation and control, and testing of the IPB power system configuration.

4.1 Simulation Objectives

An electrical power system simulation test bed can be used for many purposes. Real time and scaled time simulations integrated with control processors can verify, validate and test control algorithms implemented in software. Also control designers and managers can synthesize control algorithms that are integrated with non-real time power system simulations. This synthesis will lead to the development of operational scenarios of the power system as well as defined control methods. Another use of a real time simulation is to test other system interfaces such as the Data Management System (DMS), expert system test beds, etc.

4.1.1 Power System Software Testing

Distributed controls software and its accompanying network require verification, validation, and testing. Normal operations of the power system such as load transients (on and off) will be tested. Also off normal operations such as faults, hardware failures which may lead to load shedding will be investigated. These operations affect the power system control algorithms to various degrees and interactions. The tests must exercise all foreseeable operational scenarios in order to validate man rated software. A software test bed is the ideal environment for such tests especially with immature software. Hardware risks will be minimized. These integrated simulation and controls tests will also verify that the hierarchical control network operates in an efficient and proper manner if the simulations operate in real time. Scaled time simulations can be used to test the software as long as the control processors are slowed properly. A real time simulator is required to provide the required computational speed and the digital and analog I/O.

4.1.2 Control Algorithm Synthesis

Software designers and managers need a tool which they can use to guide the control algorithm design, develop and evolve the operational behavior of the power system controls, analyze data network operation, and also study the distribution of control responsibilities in a distributed control architecture. Such a tool can be comprised of a real time simulation of the power system (same as in previous subsection) that is integrated with simulations of the distributed control architecture. Engineers may modify this control model to describe the control design in question. Also managers can play *what if* games when evaluating designs for approvals. The control models will be designed modularly so that various algorithms may be interchanged with each other which will improve their ease of use. This type of simulation need not run in real time since it is only a stand alone analytical tool.

4.1.3 External System Interfaces

A power system test bed is needed to identify possible interface problems with external systems as well as demonstrate their functionality. A real time simulation of the power system can be used to provide this need. This test bed simulation would be similar to the one described in section 2.1 except that it must be real time. The primary control processor would have a digital network interface so that it can communicate with external systems. These systems include the Data Management System (DMS) and an expert system dedicated to power. The expert system will be responsible for demonstrating the application of Artificial Intelligence to the power system in the areas of hardware failure diagnostics, failure sensing, failure isolation, power system operator aides (i.e. displays), load scheduling, power system reconfiguration, etc.

4.2 Simulation Configuration

All simulations developed will be targeted to the Integrated PMAD Breadboard (IPB). The IPB is a second generation hardware test bed that is configured to look very similar to the current Space Station power system design. It will incorporate the control developments from the Power Management and Controls test bed (PMAD/SD test bed) and also the inverter development from the General Dynamics Breadboard (PMAD/PV test bed). Refer to section 3 for more details on the distribution and controls architectures of the integrated PMAD breadboard.

In the area of simulation of the IPB there are needs for non-real time as well as real time simulations. The non-real time simulations will simulate a full system including controls; however since real time simulation is a new effort these simulations will be reduced order simulations of simplified configurations and eventually evolve in to full system configurations.

4.2.1 Non-Real Time Simulations

Non-real time simulations may be used as a tool to develop control strategies for the power system. Since these simulations need not be real time they may model the complete IPB configuration as shown in Figure 7. If such a simulation is too large (i.e. frame time) it may be reduced to a single channel system as shown in Figure 9. This simulation would consist of all components in the full system.

4.2.2 Real Time Simulations

Real time simulations will be used for several purposes as outlined in section 2. Since the area of real time simulation of a distributed power system has not been investigated in a digital environment, the configuration of the model will evolve over time. Also the fact that the actual controllers will be interfaced with such simulation complicates the problem. Initial configurations will interface components and/or subsystems with controls as shown in Figure 8. These configurations will grow to the full Integrated PMAD Breadboard if technically possible. These power system simulations are I/O intensive because of the distributed nature of the design and also because of the variety and number of user loads in the system. In future simulations the number of loads is expected to grow tremendously.

4.2.3 Controls Configuration

The controls architecture for the Integrated PMAD Breadboard is discussed in section 3.2. The controls used in the simulation/controls test will be identical to those used in the hardware test bed. This will allow commonality of software and test results. There may be some modifications required in the Power Management Controller (PMC) for the interfacing of external systems such as expert systems and the DMS.

4.2.4 Interfaces

The interface between a real time simulation and the power management and distribution controls will define the capabilities of the simulation test bed. At this time the test bed is intended to test all controller software. Referring to Figure 8. of the controls architecture this includes all software down to the assemblies such as the MBSA, PDCA, ACSA, and DCSA. Therefore the network communications from the assembly (i.e. MBSA, PDCA, etc.) controllers to the associated switchgear will not be tested. Currently this network communication is a 1553B data bus connecting sensors in the switchgear and the assembly controller. This level of interface will drive the simulation frame time based on the software cycle times in the processors. The hardware design of this interface is flexible. It must be designed to

be low cost because of the distributed nature of the switchgear and also must communicate data in a fashion representative of the real system.

4.3 Simulation Testing

There are three major areas of simulation testing which correspond with the simulation objectives. Each of these areas has specific tests that can be performed. The following sections will discuss some of these tests.

4.3.1 Power System Software Testing

The area of power system software testing will require tests to be performed on all possible operating scenarios. These include operations during on orbit buildup, on orbit testing, normal on orbit operation, and abnormal on orbit operation.

The space station will be assembled on orbit incrementally therefore the software controls will require upgrading at various times. Each upgraded version must be tested in their normal and abnormal operations.

As the space station is assembled all hardware will be tested on orbit. Included with the operational software will be hardware test software. Again tests must exercise all operational modes.

The daily normal operation of the power system covers areas such as system monitoring, load management, communications interchange with the Data Management System, and scheduled power system maintenance. The controls software will monitor the power generation, storage, and distribution subsystems. Space Station loads need to be scheduled based on predefined priorities and also power must be provided to the loads via the switchgear at scheduled times. The Power Management Controller needs to communicate with the DMS to pass on power system status, receive load requirements for power, etc. The power system will under go scheduled maintenance periods during which power availability may drop. The power system has been designed with enough redundancy that this will occur infrequently.

The abnormal operation of the power system covers areas such as faults in the power generation systems, power distribution systems, and in the loads. Also included are unscheduled maintenance due to component failures. Power system faults may be abrupt or soft in nature. The controls system will monitor for either problem. Once detected, corrective action will be taken to clear the problem. This corrective action may cause loss of power in which loads will be taken off line or the distribution system may be reconfigured without loss of power. Again similar to scheduled maintenance, power availability may drop. In the case of unscheduled maintenance, loads may be dropped off line depending on the situation.

4.3.2 Control Algorithm Synthesis

Testing of a simulation of the power system integrated with controls (in simulation language) is less formal when used as a control algorithm synthesis tool. The objective of the testing is to ascertain whether the control algorithm will operate properly and is distributed properly within the control system. Tests will probably consist of general power system operational modes such as load shedding, fault detection, fault isolation, bus reconfiguration, etc.

4.3.3 External System Interfaces

As mentioned in section 2.3 external interfaces to external systems such as the Data Management System and expert systems will be demonstrated. The data interfaces between these systems will be tested. In the case of the DMS communications such as status reporting and command acknowledgement will be

exercised. For the expert system communications will also be analyzed and tested. Interactions between the various systems will also be explored.

5 Facility Configuration

An extensive simulation facility is needed to meet all the objectives covered in section 2. Figure 10. shows a preliminary layout of such a facility. The core of the facility is a real time digital simulation capability. The simulator is interfaced with the power system controls via a patching system. External systems such as the DMS and the expert system will be interfaced to the Power Management Controller. A human interface will close the loop between the DMS and the simulator (load requests and power usage). Output of this facility will be viewed by testers via the DMS Multi-Purpose Applications Consoles (MPACs), add on hardware such as stripchart recorders, scopes, etc.; and also the simulation graphics monitoring capability.

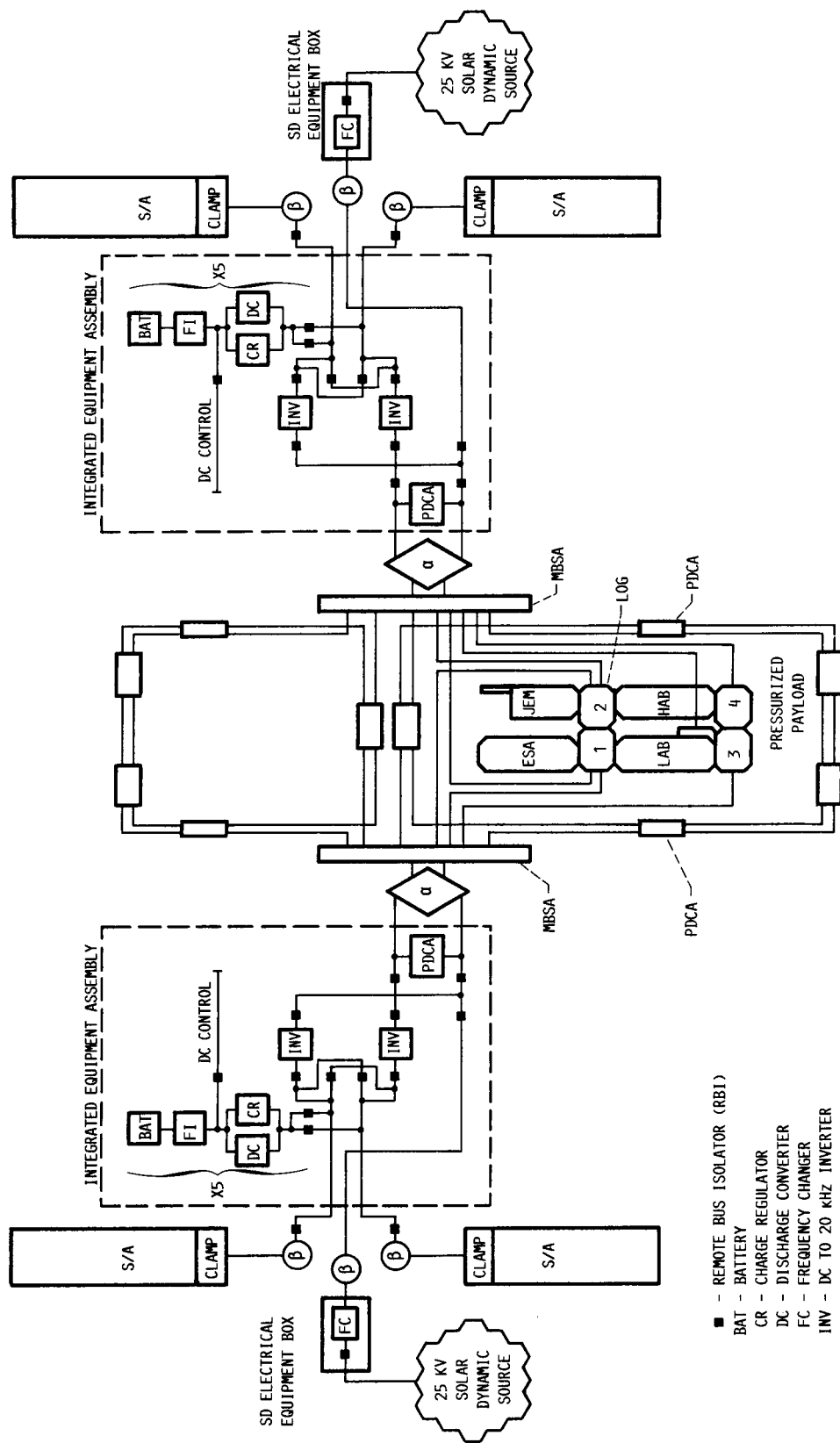


FIGURE 1. - PRIMARY POWER ARCHITECTURE.

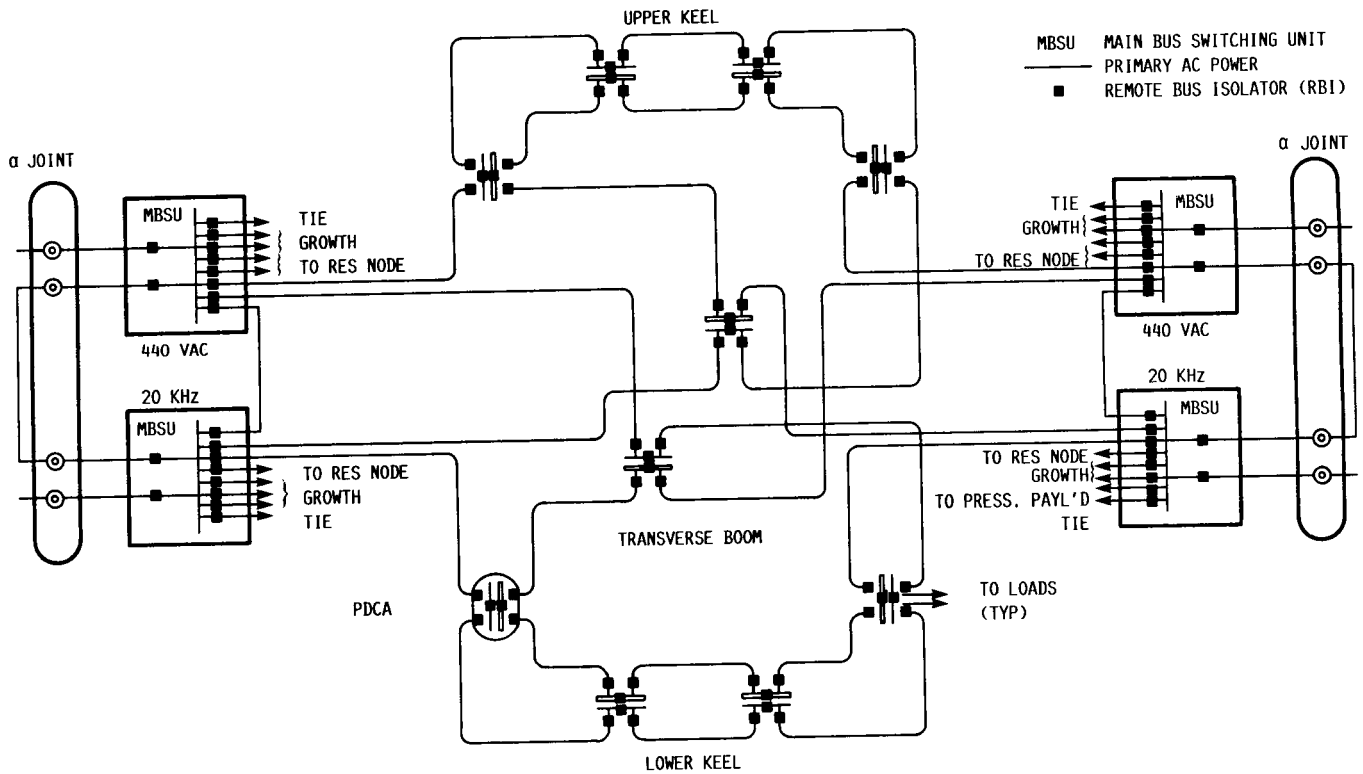


FIGURE 2. - SPACE STATION RING DISTRIBUTION SYSTEM (EXTERNAL LOAD AREAS ONLY).

AIRLOCK



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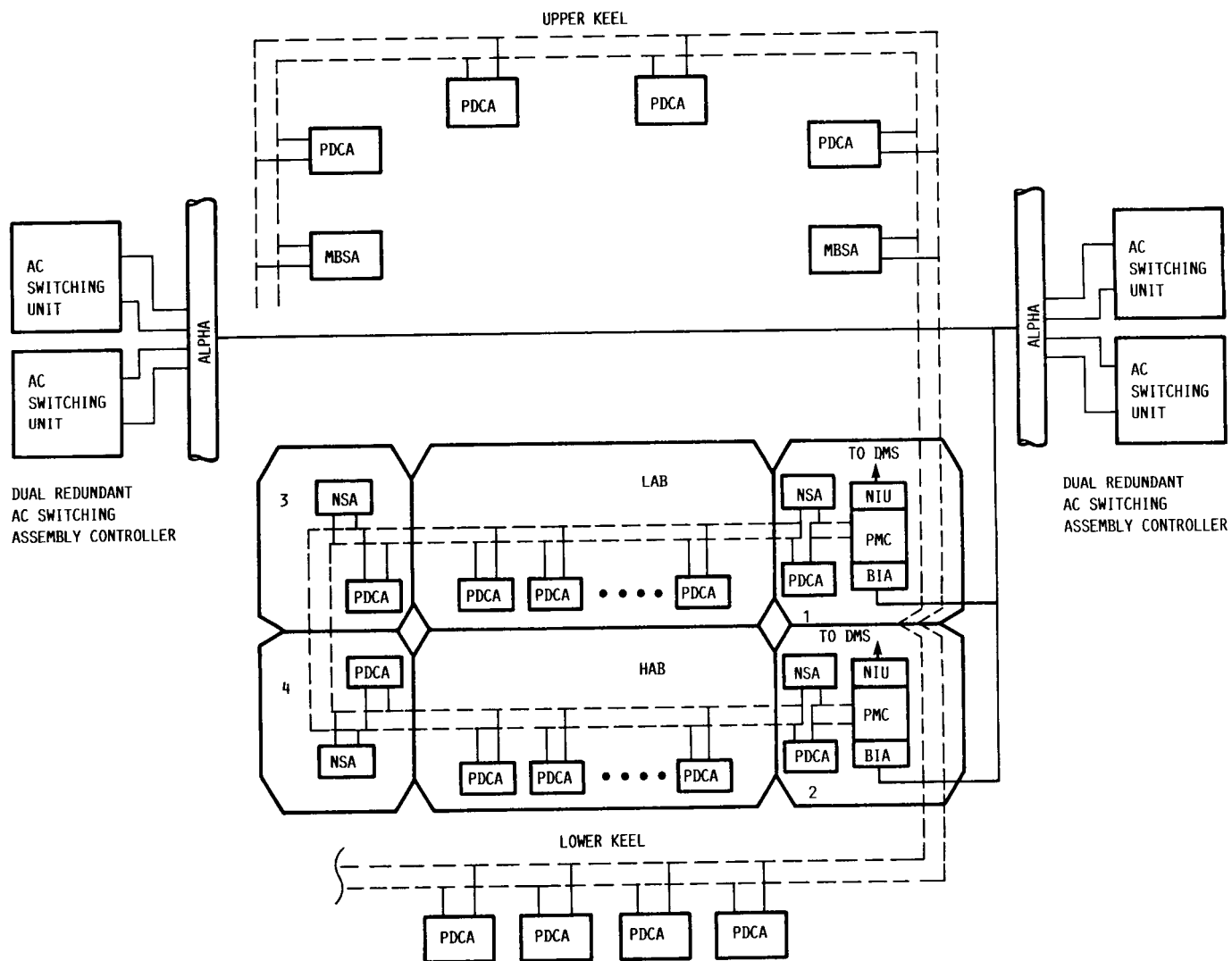


FIGURE 4. - POWER MANAGEMENT ARCHITECTURE DUAL KEEL.

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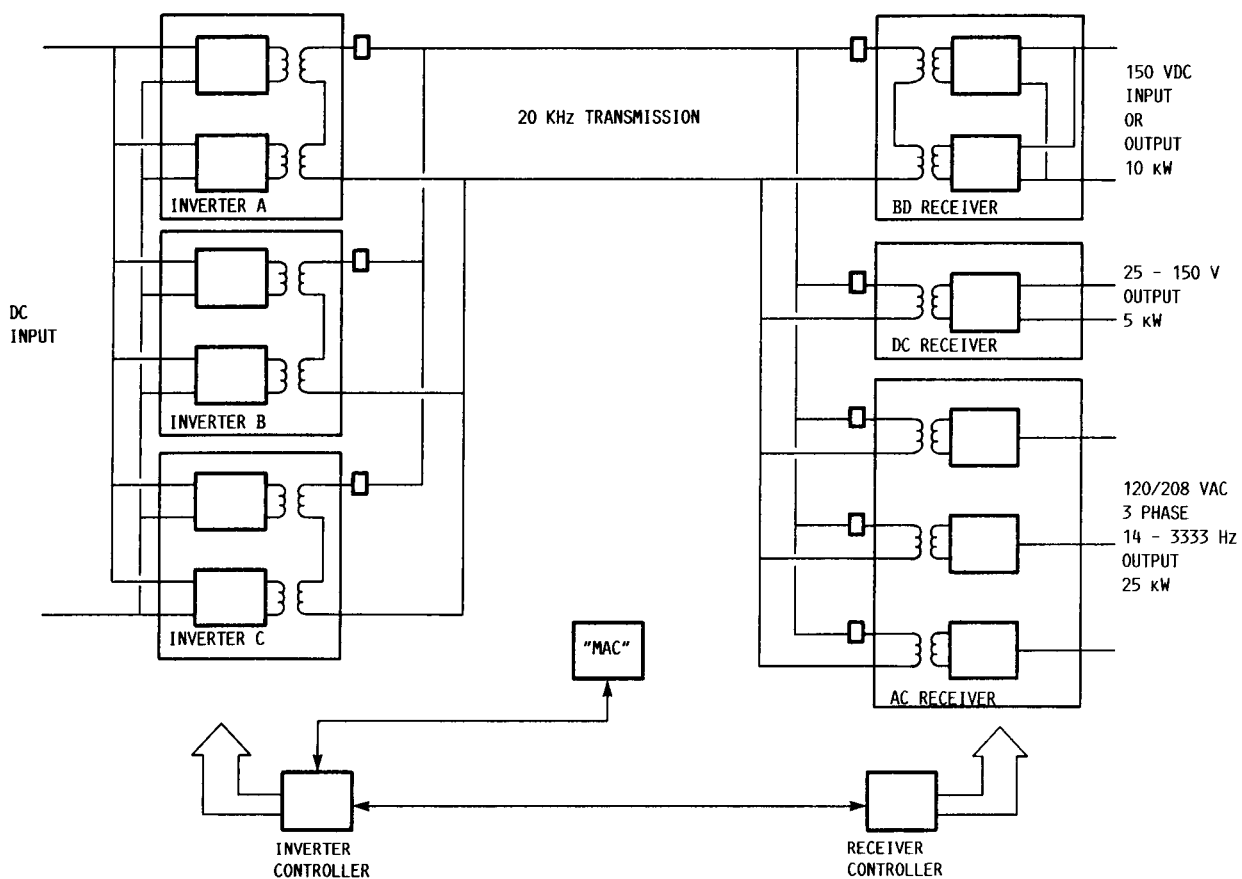
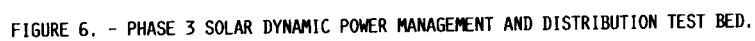


FIGURE 5. - 20 KHz PHOTOVOLTAIC TEST BED.



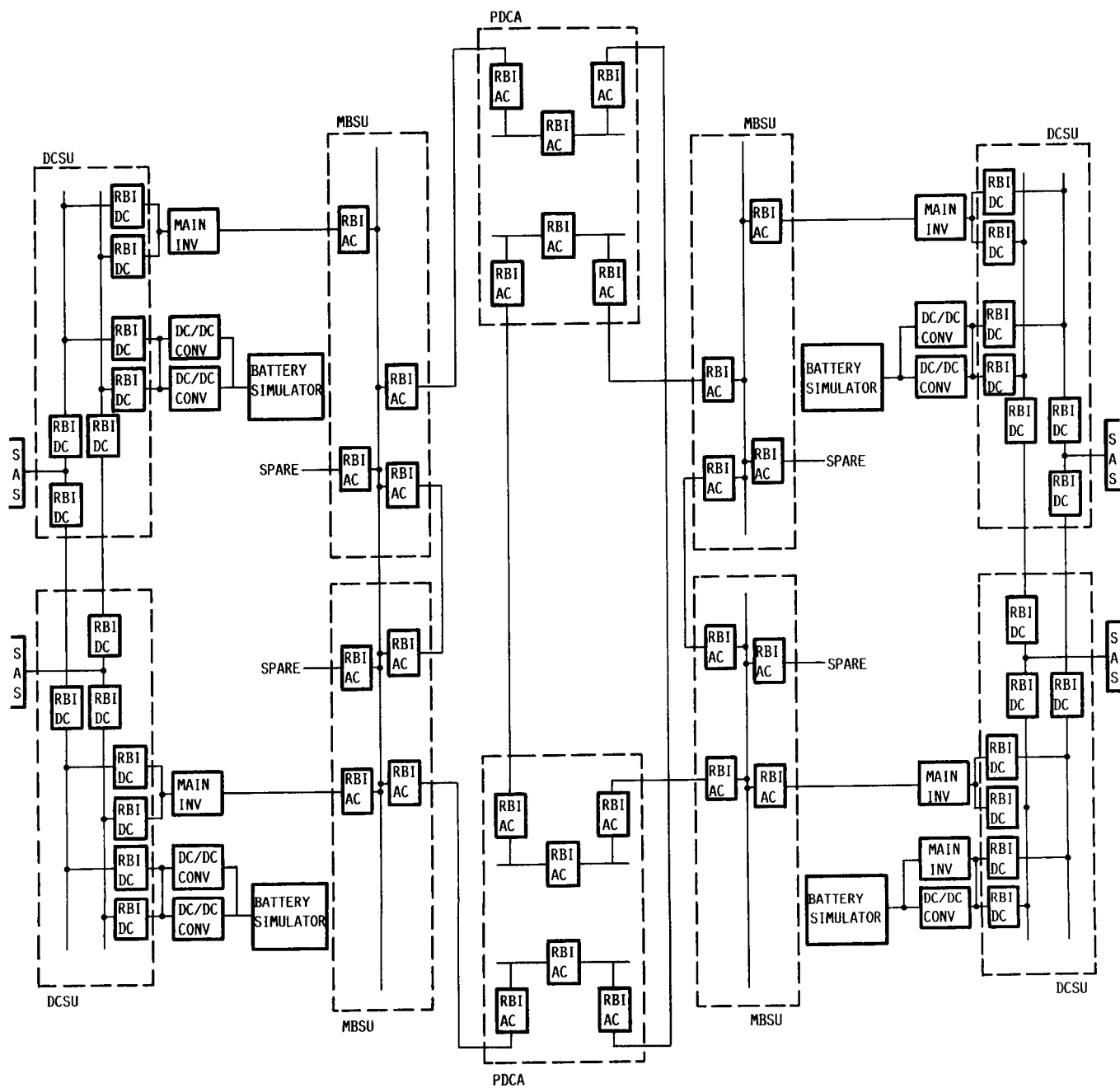


FIGURE 7. - PROPOSED INTEGRATED PMAD BREADBOARD DISTRIBUTION ARCHITECTURE.

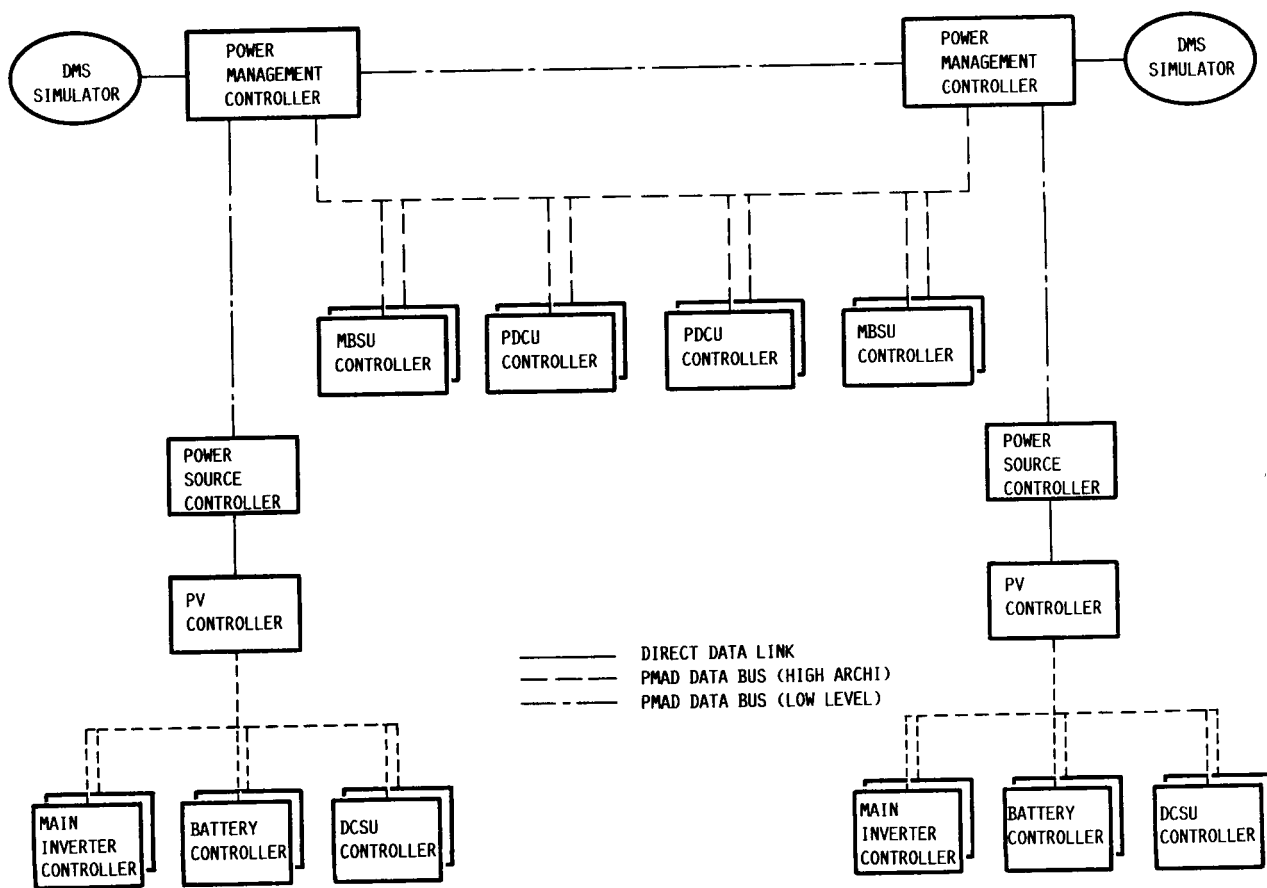


FIGURE 8. - PROPOSED INTEGRATED PMAD BREADBOARD CONTROLS ARCHITECTURE.

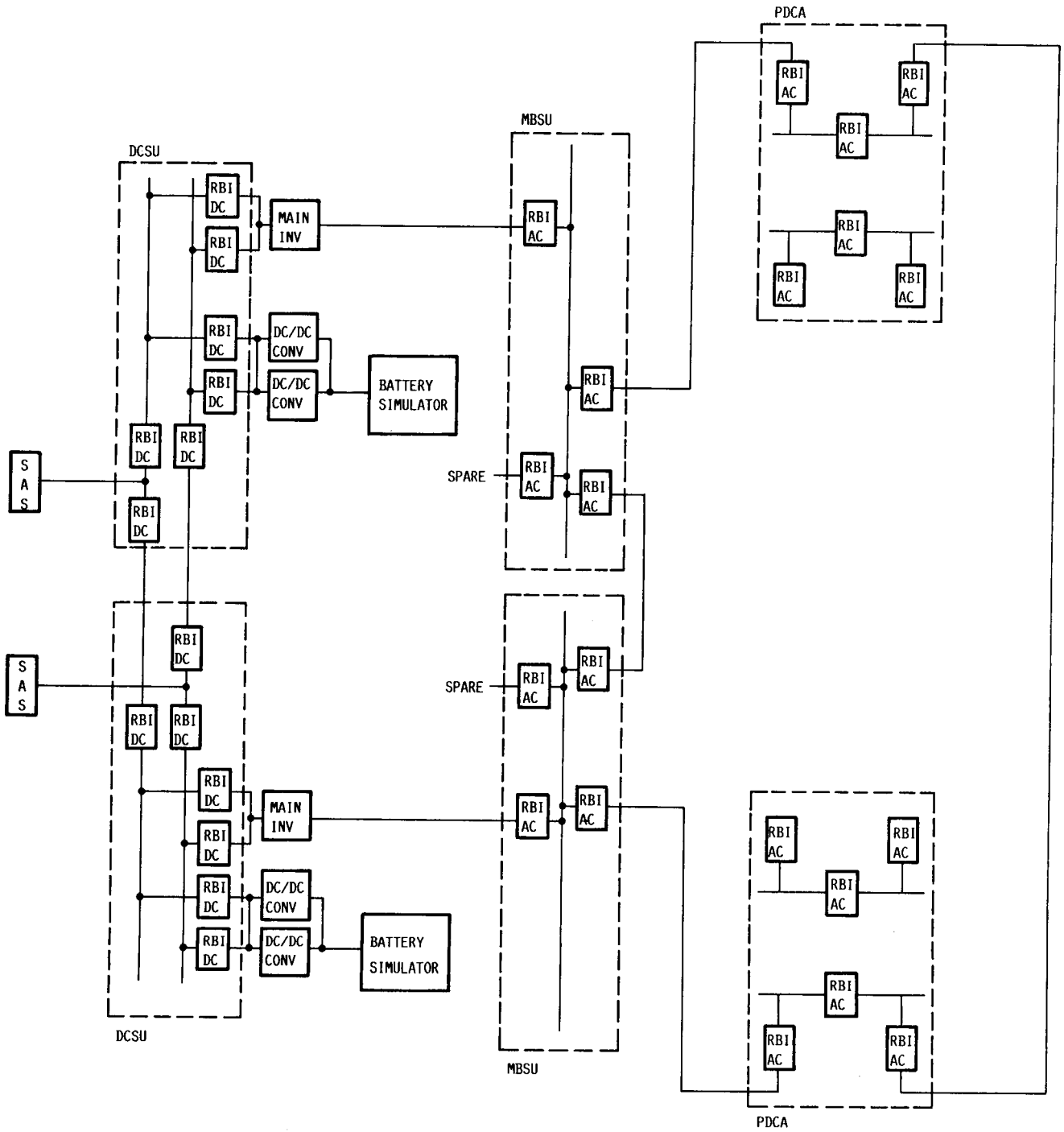


FIGURE 9. - SINGLE CHANNEL INTEGRATED PMAD BREADBOARD.

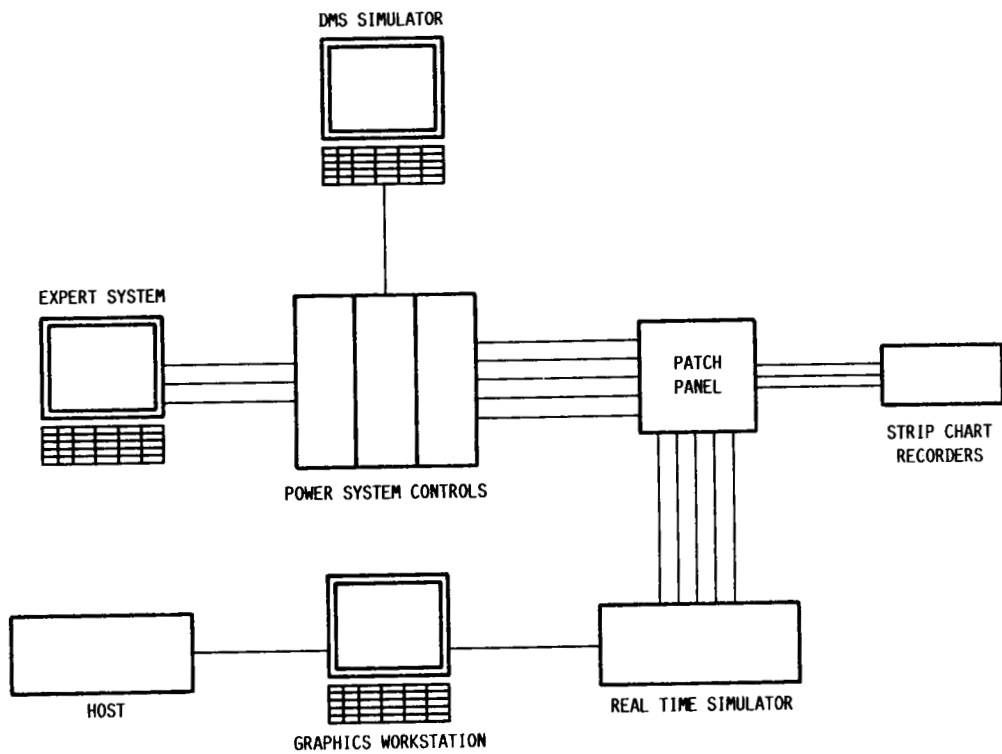


FIGURE 10. - REAL TIME SIMULATION FACILITY.



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